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SURVEY OF RESEARCH INTO ELECTROMAGNETIC AND OTHER WAVE EFFECTS ON MECHANICAL BEHAVIOR AND PROCESSING OF MATERIALS

George Mayer
Benjamin Tao

January 1992

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In an effort to assess trends in the general areas of energy effects on materials, a survey was conducted for the period 1960-1990 of the open literature sources with special focus on electromagnetic and other wave phenomena. This survey has not treated nuclear, laser, or photoplastic effects. The statistics and trends in activity have been examined in four main areas: electric fields and currents, ultrasonics, microwaves, and magnetic fields. These energies have been found to affect the structure and mechanical properties of materials, and the changes, some of them substantial, are a main subject of this survey. In addition, beneficial effects, ranging from minor to significant, have been measured during the processing of materials with these energies. It is expected that future understanding and exploitation of these effects will be essential to the widespread development and use of future DoD systems such as electromagnetic guns, toward achieving economics of manufacturing through microwave processing of ceramic armor components and thick-section structural composites, and in other applications.

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In an effort to assess trends in the general areas of energy effects on materials, a survey was conducted for the period 1960-1990 of the open literature sources with special focus on electromagnetic and other wave phenomena. This survey has not treated nuclear, laser, or photoplastic effects. The statistics and trends in activity have been examined in four main areas: electric fields and currents, ultrasonics, microwaves, and magnetic fields. These energies have been found to affect the structure and mechanical properties of materials, and the changes, some of them substantial, are a main subject of this survey. In addition, beneficial effects, ranging from minor to significant, have been measured during the processing of materials with these energies. It is expected that future understanding and exploitation of these effects will be essential to the widespread development and use of future DoD systems such as electromagnetic guns, toward achieving economics of manufacturing through microwave processing of ceramic armor components and thick-section structural composites, and in other applications.

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I. INTRODUCTION

During the past several decades, the expanding use of energetic phenomena has been demonstrated in widespread applications, from concepts involving electromagnetic guns to microwave communications (and cooking), the use of magnetic fields in medicine and in materials processing, and the employment of ultrasonic methods for nondestructive evaluation of critical defense components and in many other end uses.

Machines and devices have been developed to generate electrical, magnetic, ultrasonic, and other wave phenomena over a broad range of waveforms, frequencies, and amplitudes. Lagging somewhat behind these practical developments has been the mechanistic understanding of the effects of such waves upon the structure, properties, and processing of materials.

In order to assess the trends in activity in the general areas of energy effects on materials, a survey has been conducted for the period 1960-1990 of open literature sources. The emphasis has been on the effects of energetic phenomena on mechanical behavior of materials and on the use of such energies in materials processing.

The survey has not treated nuclear, laser, or photoplastic effects. The statistics and trends in activity have been examined in four main areas: electric fields and currents, ultrasonics, microwaves, and magnetic fields.

The major areas searched for this review included both the scientific fundamental information bases and those dealing with technological applications.

Lower level energetic methods employing electromagnetics, ultrasonics, and optical characterization procedures fall into the category of nondestructive evaluation. These levels of effects were judged to not substantively perturb or otherwise alter existing properties, defect structures, or microstructures and are not powerful enough to be considered for forming or other like processes. Work along the lines of nondestructive evaluation has not been included in the survey.

Probably more was known about the interaction of ultrasonic energy with and its influence on structure and properties of materials (prior to 1960) then was the case with the

other three areas surveyed. In terms of detailed, fundamental mechanistic understanding, more has been achieved with the electroplastic effect than with the other areas reviewed.

The following sections summarize the results of the survey according to the four areas: the effects of electric fields and currents, ultrasonic waves, microwaves, and magnetic fields upon the mechanical properties and processing of materials.

II. EFFECTS OF ELECTRIC CURRENTS AND FIELDS ON MATERIALS

A. ELECTROPLASTICITY

The main emphasis in this part of the review has been on the effects of electric fields and currents on the mechanical behavior of metallic materials (Refs. 1-187). Focus has been on the role of atomic and subatomic species, point and line defects, and the alteration of yield and flow behavior of metals and alloys. Engineering strength levels have been determined for some alloys (nonferrous light and heavy alloys, refractory metals, ferrous alloys and others) over a range of temperatures. Research is at fairly early stages on mechanical failure phenomena, including fatigue and creep. Both continuous and pulsed currents and fields have been explored.

The effect of electric current pulses on plastic flow of materials is generally known as electroplasticity. While other factors such as Joule heating and skin, pinch, and magnetostrictive effects influence the enhanced plastic deformation of metal subjected to an electric current, the major influence in the electroplastic effect is due to electron-dislocation interactions (Ref. 139). One part of this interaction is known as electron drag. Electrons, especially when moving at high speeds and low temperatures, exert a drag on dislocations. The electron drag coefficient, B_e, is defined as:

$$B_e = \frac{f/l}{V_d} = \frac{\tau b}{V_d} \qquad \text{(II-1)}$$

where f/l is the force per unit length on the dislocation,

τ is the resolved shear strength,

b is the Burgers vector of the dislocation,

and V_d is the dislocation velocity.

A second part of the electron-dislocation interaction, first proposed in 1963 by Troitskii and Likhtman, is one in which directed electrons affect dislocation movement (Ref. 139). This theory was the result of observations of significantly lower flow stresses in zinc crystals which were uniaxially deformed while simultaneously exposed to an electron beam oriented parallel to the slip plane. Troitskii concluded that drift electrons exert a "push" or force on the dislocations. This "push" has been termed the electron wind. Thus, when an electric current passes through a metal, the electron wind aids in the movement of dislocations during plastic deformation of the material (Ref. 139). In the same work, it has been shown that the electron wind contribution to the total electron-dislocation interaction comprises a majority of the effect.

There are two theoretical estimates of the electron wind force. The first is based on considerations of the specific dislocation resistivity, and the second is based on kine. or quantum mechanical considerations of the interaction between conduction electrons and dislocations (Ref. 145). Whether there are significant differences in the results of these two approaches has yet to be addressed. The electron wind force per unit dislocation length (F_{ew}) is calculated from the following in respective order:

$$F_{ew} = p_d \, e n_e j / N_d \tag{II-2}$$

and

$$F_{ew} = \alpha \, b p_f (j/e - n_e V_d) \quad , \tag{II-3}$$

where p_d/N_d (p_d is specimen resistivity; N_d is dislocation density) is the specific dislocation resistivity,

e is the electron charge,

n_e is the electron density,

j is the current density,

α is a constant ranging between 0.1 and 1.0,

b is the Burgers vector,

p_f is the Fermi momentum,

and V_d is the dislocation velocity.

From these terms for the electron wind force, one may determine the electron wind push constant ($K_{ew} = F_{ew}/j$) and the electron wind push coefficient ($B_{ew} = K_{ew} e n_e F_{ew}/V_e$).

The increase in plastic strain Γ due to the electron wind-dislocation interaction was considered by Conrad et al. for two situations: (1) when the running time t_r between barriers to dislocation movement was much longer than the waiting time t_w at each barrier, and (2) when $t_w >> t_r$ (Ref. 146). For $t_r >> t_w$:

$$\Gamma_j/\Gamma = \frac{B_e(B_e\tau_a{*}b - B_{ew}^2 V_e)}{\tau_a{*}b(B_e^2 - B_{ew}^2)} \qquad \text{(II-4)}$$

where $\tau a{*}$ is the effective externally applied stress and v_e is the electron drift velocity. The subscript j refers to the value during the current application; the omission of a subscript refers to the absence of a current. For $t_w >> t_r$,

$$\ln\Gamma_j/\Gamma = \ln(\Gamma_{oj}/\Gamma_o) - \left[\frac{Gj^* - G^*}{kT}\right] + \left[\frac{(Aj^* - A^*)\, b\tau_a^*}{kT}\right] + \ln 2\cosh\left[\frac{A^*F_{ew}}{kT}\right] \qquad \text{(II-5)}$$

where $\Gamma_o = N_{D,m} bsv^*$ (pre-exponential factor),

$N_{D,m}$ is the mobile dislocation density,

s is the average distance moved per successful fluctuation,

v* is the frequency of vibration of the dislocation,

G* is the Helmholtz free energy of activation,

A* is the activation area,

and kT has its usual meaning.

The effects of current density (j) on the ratio of the strain rate with a current ($\dot{\epsilon}_j$) to the strain rate prior to a pulse ($\dot{\epsilon}_o$) was determined experimentally by Conrad et al. It is defined as:

$$\dot{\epsilon}_j/\dot{\epsilon}_o = (j/j_c)^n \qquad \text{(II-6)}$$

where j_c is the critical current density (of the order of 10^3-10^4 A/cm^2), and n is about 3 (for tests on Al, Ag, Cu, Ni, Nb, Fe, W, and Ti) (Ref. 145).

The critical current density is found to vary for different metals as a function of the electron density:

$$j_c = C n_e^q \qquad \text{(II-7)}$$

where C is a constant that decreases with temperature, and q is of the order of 2/3 at 300 K and 2/5 at 77 K.

In studying electroplasticity in zinc crystals, Troitskii et al. measured a 10-40% reduction in load drop when a current with a density of 10^3 A/mm^2, pulse duration of 50 μs, and a pulse frequency of 0.1 Hz were applied at temperatures ranging from 78-300 K (Ref. 139). In studying electroplastic deformation of amalgamated zinc before brittle fracture, Troitskii recorded that plastic deformation to fracture increased by 100-120% at 77 K and by 50-60% at 293 K using concurrently applied current pulses of $\approx 10^3$ A/mm^2 (Ref. 29). There were increases in the true values of the normal and shear strains by 30% at 77 K and by 35% at 293 K. The current also caused an increase of the critical normal strains by 50-60% and a reduction of critical shear strains by 12-15%. Sprecher et al., with j = 5500 A/mm^2 at a plastic strain of 0.8%, measured a drop in flow stress in metals. These ranged from 1% in tungsten to 36% in aluminum (Ref. 139).

Spitsyn and Troitskii also conducted extensive experiments on the electroplastic effect on steady state creep rates of monocrystalline metals (Ref. 4); the creep rates were shown to increase. The following are the results: lead (load, P = 1.2 N/mm^2), 30%; zinc (0.3 N/mm^2), 106%; indium (0.45 N/mm^2), 49%; and tin (1.5 N/mm^2), 15% (Ref. 4). The type of current applied during the tests also affected the rate; a pulsed current (every 50 Hz) had the greatest effect. The next largest was due to a direct current, and an alternating current (50 Hz) had the smallest effect. The studies were done using $j \approx 7$-8 A/mm^2 at 77 K.

Effects of electric currents on fatigue were studied by Conrad et al. (Ref. 146). Using simultaneous current pulses of 1.3×10^{-4} A/cm^2 for 100 μs with 2 per second, the

fatigue life (N_f) of copper during a rotating bending test at 300 K increased by a factor of 1.2 - 3.0. There was an increase in the number of cycles needed for microcrack initiation and a decrease in macrocrack growth rate. Thus, both initiation and propagation phases in fatigue were extended, resulting in longer fatigue life for copper. Transgranular cracking seemed to be promoted by the current pulsing as opposed to intergranular cracking. Conrad et al. attributed the longer microcrack initiation time to increased homogenization of slip, while the decrease in macrocrack growth rate was attributed to a decrease in K_{eff} (K is the stress intensity factor; $K = \sigma\sqrt{a}\, f(a/w)$. σ is stress, a is crack length, f(a/w) is a factor which is a function of specimen geometry, and w is the specimen thickness) due to the presence of a thicker oxide film (SEM analysis revealed increased oxidation due to electropulsing) which affected crack closure.

Electric (d.c.) field effects have been studied in less detail than the effects of electric currents. During the superplastic deformation of 7475 aluminum alloy in a d.c. electric field of 2 kV/cm, Conrad et al. observed a decrease in flow stress (σ) at all strain levels (ϵ), which reduced the rate of strain hardening ($\theta = d\sigma/d\epsilon$) and increased the strain rate hardening exponent ($m = d\ln\sigma/d\ln\epsilon$) (Ref. 146). The amount of cavitation produced by the deformation was also reduced, with the reduction increasing with field strength. Grain growth retardation was observed in an electric field. The effects on the 7475 alloy were not entirely clear. The field may have affected diffusion, specifically the generation and/or migration of vacancies. Soviet work done by Kishkin and Klypin reported that an electric field (E = 100 V/cm) applied during the creep of copper and cobalt at high homologous temperatures caused an increase of an order of magnitude in the steady state creep rate (Ref. 145).

Some investigations have been conducted on the phase transformation of metals. Electric pulsing (10^5 A/cm^2, 60-95 microsecond durations, and 4.2-8.7 pulses per second) of amorphous iron-based alloys resulted in alpha-iron precipitation at temperatures below (150°C below) those where bulk crystallization occurred (Ref. 146). This enhanced rate of precipitation might result from an increase in electromigration caused by the electric current. The application of electric fields (1-2 kV/cm) applied during quench hardening and tempering of 4340 steel produced a slightly increased rate of austenization, a large increase in hardenability, and a slight retardation in the tempering rate. After 3 minutes of austenization in a 1 kV/cm field, the same level of hardness was achieved as for 5 minutes of austenization without a field. The hardenability of the steel doubled after austenization and quenching in an electric field as compared to processing without a field. An increase of

20°C was needed to achieve the same hardness during tempering in a 2 kV/cm field than without.

The study of electroplasticity has not been confined to metallic materials (Refs. 188-200). In 1984 Kulichenko and Smirnov studied the effects of electric fields in the polymers PMMA (polymethlymethacrylate), PS (polystyrene), and PVC (polyvinylchloride) (Ref. 200). The external field gradually lowered the stress applied during deformation. The possibility that the electric field caused heating of the sample during the flow of an electric current was discounted, as an estimate showed that such heating resulted in only a fraction of a degree increase in temperature. While the authors offered two possible models of the effect, it was concluded that further study was necessary before a valid theory could be formulated.

B. PROCESSING AND MISCELLANEOUS EFFECTS

In addition to mechanical property effects, a full range of other effects have had some limited study. Thermoelectric effects have been examined (Refs. 201-208). Work has been done on the effect of fields and currents on the magnetic phases of metallic materials, with much of it focused on the positive or negative shift in the Curie temperature of magnetic phases in ferroelectric and antiferroelectric materials (Refs. 209-237). Some initial work has been done on the effects of electric currents and fields on electrical properties of materials (Refs. 238-280) as well as the effects on the magnetic properties of materials when fields were applied during processing (Refs. 281-297). Solidification and growth of metallic materials in currents and fields has been examined. During electropulsing of copper, a doubling of rates of recovery and recrystallization were observed (Refs. 298-333). Conrad et al. have determined that the enhanced rates of recrystallization observed were the result of the current's effect on the rate of subgrain formation and coalescence; it increased the rate of annihilation of residual dislocations (Ref. 146). Annealing in a field resulted in an opposite effect. The annealing temperatures of copper and aluminum in an electric field were moderately higher than without a field. Optical properties affected by electric fields and currents such as luminescence, optical absorption, fluorescence, and photoconductivity have been the subjects of limited study in the last few years (Refs. 334-358). The effect of electric fields on the rate and mechanism of polymerization of polymers has also been briefly considered, where the rate was greater or lesser, depending on the polymer (Refs. 359-362). Sakurada et al. noted increases in the rate of ionic polymerization and the degree of polymerization in electric fields, which has

been attributed to the second Wien effect (Ref. 361). Akbulut et al. reported that the rate of formation of polymers at high conversions decreases in an electric field (Ref. 361). Electrochemical effects are believed to be responsible. Electrical field and current effects during the growth and the deposition of thin films and coatings have been explored (Refs. 363-377). Electrophoretic chromium carbide alloy coatings were influenced by electric field strength on their rate of formation and chemical composition (Ref. 372). The growth rate of gallium arsenide thin films was 1.45 μm/minute in a zero potential, while it was 1.8 μm/minute in a negative potential of 1 kV when grown on a substrate oriented in a <111> direction (Ref. 377). The density of growth hillocks and pits was also reduced. Electric field effects on adhesive bonds and joints have had some isolated study (Refs. 378-380). Additional work is needed to clarify the mechanisms governing these effects and to quantify them.

C. SURVEY RESULTS

As in other areas of this survey, the contribution of Soviet investigators make up much of the research in the area of the effects of electric currents and fields. In the area of electroplasticity, Soviet scientists accounted for about 70% of the published research (Refs. 1-128). Troitskii and his colleagues were responsible for about 40% of these (Refs. 1-49). U.S. literature comprised nearly 20% of the papers surveyed, (Refs. 129-163) and Conrad and his colleagues represented about half of these (Refs. 129-146). Figure 1 shows the overall breakdown for this section by country.

The amount of interest has been climbing steadily in the last few decades. Figure 2 reveals the levels of effort between 1960 and 1989.

In Figure 3, a breakdown of the different areas explored is shown.

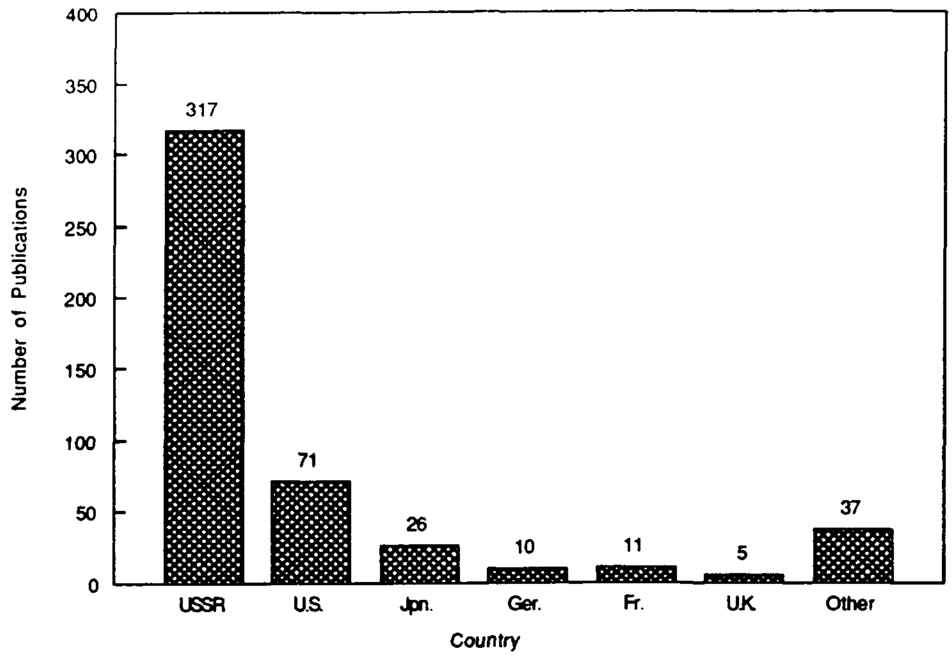

Figure 1. Published Research on Electric Current and Field Effects on Materials by Country (1960-1989)

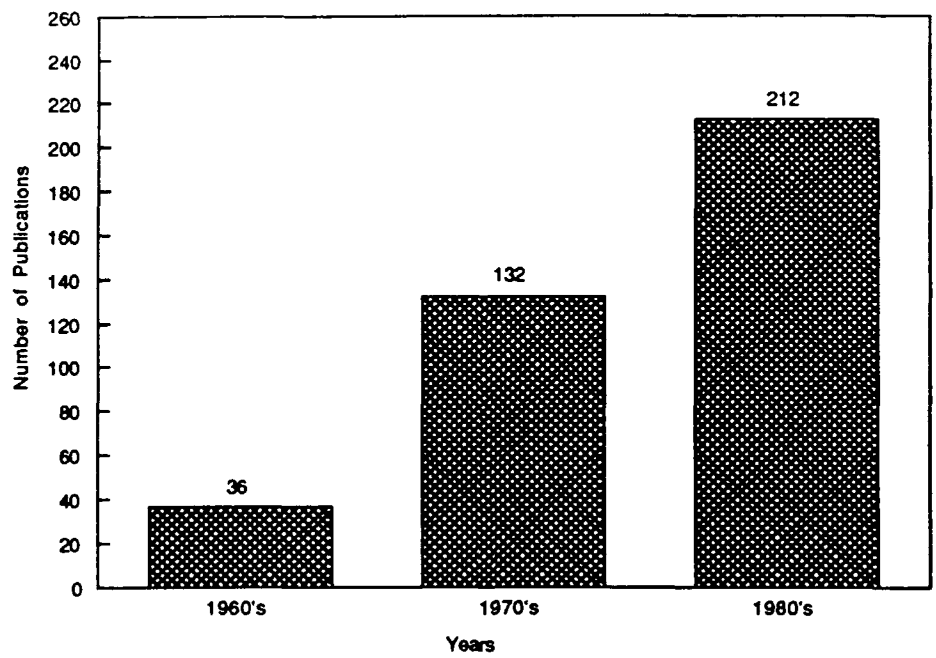

Figure 2. Published Research on Electric Current and Field Effects on Materials by Decade

Electroplasticity	(200, 52%)
Solidification and Other Phase Transformations	(65, 17%)
Electric and Magnetic Properties	(60, 17%)
Other	(55, 14%)

Figure 3. Areas of Literature Emphasis (1960-1989)

III. ULTRASONIC EFFECTS ON MATERIALS

A. EFFECTS ON STRUCTURE AND MECHANICAL PROPERTIES

An analysis of the open literature on ultrasonic effects on materials finds a marked increase in interest during the past two decades in studying the effects of this form of energy on properties and processing of a wide range of materials. The greatest emphasis is on the category of microstructure/mechanical property relations, which range from simple correlations of the applied ultrasonic energy with resultant mechanical properties, to much more detailed studies of dislocation structures and defect interactions as more sophisticated tools and methods of analysis became available (Refs. 381-445). During the past ten years, identification of micromechanisms underlying the enhancement or degradation of mechanical properties by ultrasonic waves has been of main interest. Efforts have been devoted to clarifying the effects of energy on the static and dynamic behavior and properties of (mainly) metals and alloys, including yield strength, microhardness, and creep.

The main effect which is observed as the result of ultrasonic treatment of metals is an increased concentration of dislocations (Ref. 407). This increase affects the plastic deformation and mechanical properties of metals. It has been observed that ultrasonic treatment increases the hardness of metals rapidly. Bazelyuk et al. reported a 19% increase in microhardness in Kh16N11M3 stainless steel ($Cr_{16}N_{11}Mo_3$ stainless steel) after 5 minutes of ultrasonic excitation (20 kHz and a maximum amplitude of alternating mechanical stresses of 12 N/mm^2) (Ref. 390). After this maximum treatment time, the microhardness decreased rapidly, indicating work-softening. After 10 minutes of treatment the microhardness decreased 12.5% from the original value (Ref. 390). Bazelyuk et al. attributed this loss of strength to an increase in the concentration of vacancies, causing dislocation annihilation and rearrangements, and easing formation of polygonal subgrains (Ref. 390). Vasudevan and Muralidhar also observed an increase in hardness of solution heated-treated aluminum alloys of 40% after 5 minutes of treatment with 35 watts/cm^2 at room temperature (Ref. 412). Increased rates and higher values were found at higher temperatures. The same amount of hardening by natural aging would have taken 24 hours (Ref. 412). The amount of hardening asymptotically approached a horizontal line for most treatment temperatures. The authors attributed this to a large increase of the dislocation

density which allowed greater amounts of finer precipitation at nucleating centers. These centers acted as pinning points for dislocations. However, at 180°C for alloy Al-Zn-Mg and at 160°C for alloy Al-Cu-Mg, the hardness dropped rapidly after 1 minute of exposure, similar to the results reported by Bazelyuk et al. (Ref. 412). The yield stress for metals subjected to ultrasonic treatment increased, with the resulting improvements varying. After a cyclic heat treatment (50 cycles) between 650°C and 20°C followed by an ultrasonic treatment of 5 minutes and a peak value of mechanical stress of 12 N/mm^2, the yield strength of Kh16n11m3 stainless steel increased by 33% (Ref. 390). Treatment of Al-Zn-Mg alloy with an ultrasonic energy of 35 $watt/cm^2$ at 150°C for 10 hours resulted in a 218% increase in yield strength (Ref. 412). The elongation dropped from 25% to 12% during the same treatment.

The effect of ultrasonic energy applied during the *simultaneous* application of a load has also been studied. A 40% drop in tensile strength (Ref. 430) has been obtained in zinc single crystals exposed to ultrasonic emissions (25 watts maximum power at 800 kHz). Upon removal of the ultrasonic load, the tensile load returned to its previous value. Some have attributed this softening of the metal to a simple superposition of the alternating ultrasonic stress onto the externally applied stress. In the same 1989 paper, Green suggested three variables as possible underlying reasons for this effect, all of which were components of an equation defining stress (σ) during a standard tensile test:

$$\sigma = \frac{st - \epsilon_p l}{A/K + 1/E^*} \qquad \text{(III-1)}$$

where

s is the crosshead speed,

t is the time,

ϵ_p is the plastic strain,

l is the specimen length,

A is the specimen's cross-sectional area,

K is the compliance of the load cell spring and frame of the tensile machine,

and E^* is the effective Young's modulus of the specimen.

In order for the observed stress drop to occur, one or more of the following things must happen: (1) 1 increases, (2) E^* decreases, and/or (3) ϵ_p increases.

The length of the specimen grows as the crosshead moves at a rate of s. Yet, if the ultrasonic emissions cause the length to increase beyond the limit which is a function of s, then the force on the load cell would decrease. For E^* to decrease, many factors would have to be responsible. One factor is the reduction of E^* as a linear function of increased tensile stress, for which Green has derived an expression. The increase in ϵ_p as a cause seems to be more generally accepted. It might be caused by the ultrasonic energy interacting with dislocations, multiplying and activating them. The resulting movement of dislocations would increase plastic strain. More comprehensive details of this proposed reason for the stress drop are not yet available.

The acceleration of the rate of creep during exposure to ultrasonic emissions during testing has also been observed. Initial creep rates grew exponentially as the ultrasonic stress amplitude increased (Ref. 388). Ultrasonic treatment of aluminum *before* creep testing yielded a different result. After a treatment at 260°C at an ultrasonic stress amplitude of 0.96 N/mm^2, the creep rate from zero to 7 minutes varied cyclically. The rate after 30 seconds of exposure decreased 62% (Ref. 412). After 2 minutes, the rate had increased by 40% from the original (Ref. 412). At 4 minutes, the rate had again dropped by 62% of the original (Ref. 412). Thus, selective treatment of these aluminum alloys can allow an improvement in the creep rate.

Fatigue testing using ultrasonic oscillations has been performed to gain further understanding of fatigue based upon dislocation concepts (Refs. 431-445). The results have been used to test fatigue theories which have been based upon conventional fatigue testing.

B. PROCESSING AND MISCELLANEOUS EFFECTS

Early attention was attracted to the use of ultrasonics for the processing of materials through the practical success shown by its application to wire-drawing of hard-to-form metallic materials in the 1950s by AT&T (Refs. 446-449). Ultrasonic die activation allowed a reduction in drawing force which varied with drawing rate. A maximum of 75% reduction in force at below 10 feet per minute drawing speed down to a 5 to 10% decrease in force at drawing rates approaching 1000 feet per minute with copper and steel wire have been demonstrated (Ref. 437). A follow-up to this research showed the advantages of tube drawing by axial oscillation of the plug. Reductions in average drawing force were 4-30%

for aluminum alloys, 1-14% for steel, and 2-12% for titanium alloys (Ref. 437). A smooth drawing (absence of slip-stick) resulted from the process, especially for titanium; such results were unlikely with conventional techniques.

Along other technological avenues, ultrasonics have been explored for welding and other bonding processes, largely in metals during the 1970's; but, in the 1980's, more in polymers and in special configurations and complex materials, such as laminates (Ref. 450-481). Reduced costs and energy conservation in reference to adhesive bonding have been demonstrated in the use of ultrasonic bonding of reinforced metal (aluminum/titanium) composites employed in aircraft structures (Ref. 475). Ultrasonic welding has been studied for use in thermoplastic processing. Thermoplastics, which offer some advantages over thermosets, are limited in part complexity because of their forming processes. Ultrasonic welding offered the strongest bonds between thermoplastics (Ref. 458). Ultrasonics have been utilized for cleaning a wide variety of materials (Refs. 482-489), including metallic alloys (Ref. 489), beer kegs (Ref. 482), electronic substrates (Ref. 488), and precision glassware (Ref. 484). It has also been considered for the application of de-inking certain wastepapers which cannot be de-inked using conventional chemical methods (Ref. 486). In the areas of casting and solidification, ultrasonics were applied to metal processing (Refs. 490-499) in the 1970's during such methods as ingot solidification in continuous casting which resulted in a uniform and fine grain structure (Ref. 498). Ultrasonic excitation during the atomization of metal powders resulted in high dispersion and homogeneity, a spherical particle shape, and low (<0.02%) oxygen content (Ref. 495).

More recently, ultrasonics have been used in polymer, composite, and concrete processing (Refs. 500-509). Ultrasonic treatment has been shown to be a decisive factor in structure formation of cement paste (Ref. 509) while ultrasonic treatment of cold-solidifying plastic solutions can be used in the manufacture of plastic-metal composites (Ref. 493). The use of ultrasonics in this manner can reduce production time by factors of 2-5. Ultrasonic oscillations have also been shown to strengthen composite materials (Ref. 503). Transversal reinforcement with microparticles of polymer composites can increase the transverse tensile strength by factors of 1.8-2.5 and stiffness by 40-60%. The widespread use of this method, however, is hampered by the increase in static forces necessary to embed the microparticles. The superposition of ultrasonic vibrations on the static force can improve this transverse reinforcement method. Tomashevskii et al. concluded the ultrasonic vibrations can intensify the reinforcement process significantly while simultaneously reducing the effect of the materials resistance forces to the embedment

of the microparticles by a factor of three-fourths without a reduction in composite quality. Ultrasonics have been utilized during the past several years during the deposition of plated and other protective layers (Refs. 510-512), e.g., during electrolytic deposition of lustrous nickel. The ultrasonic treatment increased the hardness of the coating (Ref. 511). An ultrasonically assisted coating of aluminum with zinc resulted in a homogeneous layer, while a coating without an ultrasonic treatment was inhomogeneous (Ref. 512). Another important area of application has been in machining (Refs. 513-530). Ultrasonics have been used in the accelerated grinding and drilling of ceramics with a minimum of residual stresses; such removal methods are difficult to do by conventional means due to the hardness of most ceramics (Ref. 522). Ultrasonics displayed high removal rates and low machine wear (<0.5%) in the machining of graphite electrodes, (Ref. 524) and ultrasonic knives are being used to cut composite helicopter blades (Ref. 513). Finally, the effect of ultrasonic energy on the electrical and optical properties of materials have been the subject of scattered studies (Refs. 531-541).

C. SURVEY RESULTS

With these technological applications has come a variety of new equipment for processing and testing, as well as several monographs which have reviewed both the fundamentals and the applications of ultrasonics (Refs. 542-553). Several Russian authors have published books on the theory of ultrasonics. An article on a machine to be used for the ultrasonic welding of aluminum cans has been published (Ref. 547). Setting up a microprocessor assembly line using ultrasonics has also been described (Ref. 553).

It is interesting to note that the Soviet researchers again accounted for a large percentage of the work done in this area, about half of it (Refs. 381-411). Figure 4 shows the level of effort by country on the research into ultrasonic effects on materials.

The level of work in this area has also grown steadily, as shown in Figure 5.

Figure 6 shows the areas of emphasis of research.

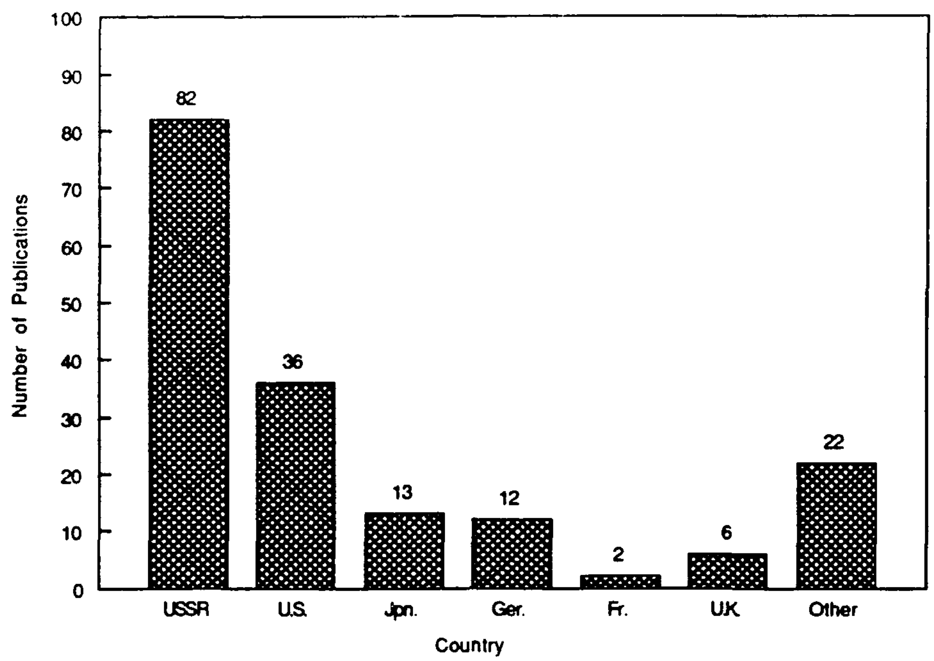

Figure 4. Published Research on Ultrasonic Effects on Materials by Country (1960-1989)

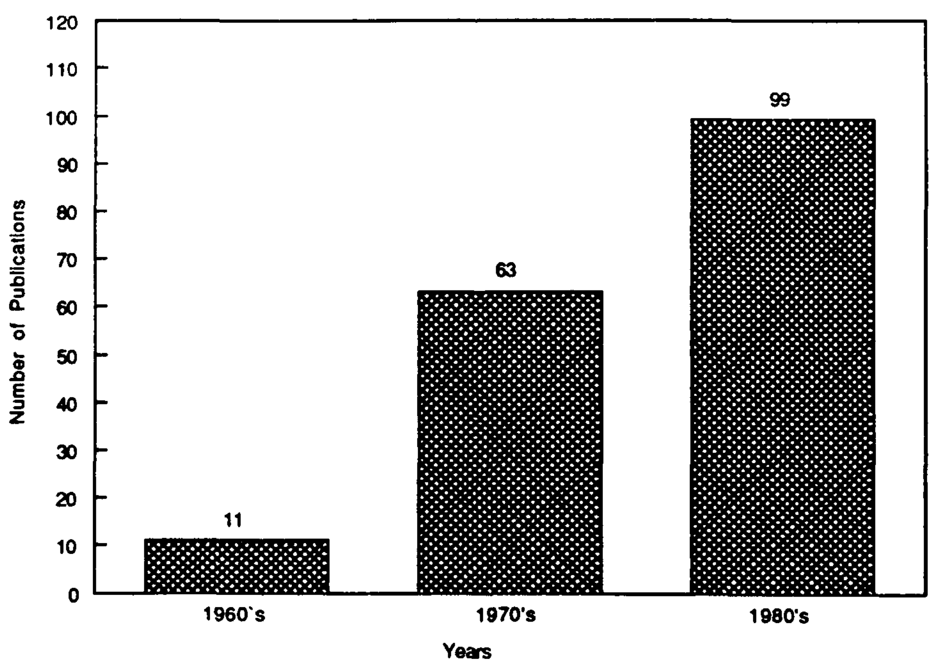

Figure 5. Published Research on Ultrasonic Effect on Materials by Decade

Mechanical/Structural Effects	(65, 38%)
Bond/Weld	(32, 18%)
Other Processing	(24, 14%)
Machining/Coat/Clean	(29, 18%)
Miscellaneous	(22, 12%)

Figure 6. Areas of Literature Emphasis (1960-1989)

IV. MICROWAVE EFFECTS ON MATERIALS

The number of reported studies on the effects of microwaves on materials processing and properties has increased during the past decade. However, no references were cited in the decade from 1960-1970. Because of the unique heating characteristics of microwaves, most of the attention in the scientific and technical literature has been on the processing aspects of microwave interactions with materials. In the early 1970's, the first use of microwaves for drilling fine holes in ceramic wafers was reported (Refs. 554-555). Microwave micropiercing of ceramic wafers is preferable to conventional machining techniques because of the brittleness of ceramics. The microwaves dielectrically heat, melt, and vaporize these materials; conventional drilling may cause problems such as chipping. Early effects of microwaves on semiconductors were cited in the Soviet literature (Refs. 556-557) and on optical materials in the United States (Refs. 558-559). Two references to biological effects were also reported in this time frame in the nonmedical literature (Refs. 560-561).

Chabinsky (Ref. 561a) has reviewed present uses and future projections of microwaves in materials processing. For ceramics, a wide variety of applications in drying, slip casting, calcining and sintering were foreseen over the 5-year period from 1988-1993. Interesting and potentially important uses for microwaves in re amation (rubber, oil, asphalt) and in pollution control (disulfurization of coal, breakdown of hazardous materials) were addressed. In the medical/biological area, expanded uses were predicted in the areas of sterilization and waste treatment, and in the broad area of elastomers, polymers and composites, forming, drying, and curing were anticipated to be improved to commercially significant levels. For polymeric materials, McGrath and his colleagues (Ref. 561b) have demonstrated orders-of-magnitude time savings in processing with equivalent or improved mechanical properties (compared with conventional thermal treatments).

A. MICROWAVE SINTERING

The first published use of microwaves for sintering of ceramics was in France in the later 1970's (Ref. 562). During the 1980's, most of the reported literature on

microwaves focused on sintering behavior of structural ceramics, along with others on piezoelectric and photovoltaic materials (Refs. 563-594).

The interaction of microwaves with materials is dependent on the dielectric and magnetic properties of the material being processed. This results in a strong dependence of power absorption on frequency, particle size of the material, shape, temperature, and density. An electromagnetic wave, E, which is dependent on space, time, and materials properties, may be defined as

$$E = f(x,y,z,t,\varepsilon,\mu) \text{ (Ref. 594)} \tag{IV-1}$$

where

x, y, and z are distance coordinates in space,

t is time,

ε *is permittivity, and*

u is permeability.

In terms of wave-material interactions, the properties of a material that are most *important are the permittivity and the permeability. These are:*

Permittivity: $\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon_0 (\varepsilon''_{eff})$ (IV-2)

Permeability: $\mu^* = \mu' - j\mu'' = \mu_0 (\mu'f - j\mu''_{eff})$ (IV-3)

where: ε' = dielectric constant

ε'' = loss factor

ε'_r = relative dielectric constant

ε''_{eff} = *effective relative loss factor* = $\varepsilon''_r + \sigma/\varepsilon_0\omega$

ε''_r = relative loss factor

σ = conductivity

μ' = permeability

μ'' = magnetic loss factor

μ'_r = relative permeability

μ''_{eff} = effective relative magnetic loss factor.

The wavelength, λ, of the electromagnetic wave decreases according to (Ref. 561d)

$$\lambda = \frac{\lambda o}{\sqrt{\varepsilon_r'}} \text{ (for } \varepsilon''\text{eff} << \varepsilon_r') \qquad \text{(IV-4)}$$

and the field is attenuated

$$E = E_o \, e^{-\alpha Z} \text{ (propagation in Z-direction)} \quad , \qquad \text{(IV-5)}$$

where α: attenuation constant

$$\alpha = \frac{\sigma}{2} \left\{\frac{\mu}{\varepsilon}\right\}^{1/2} , \text{ when } \frac{\sigma}{f\varepsilon} < 1 \quad . \qquad \text{(IV-6)}$$

When the attenuated wave transfers thermal energy into the material, heating occurs, and power is dissipated according to (Ref. 561b)

$$P = Kf\varepsilon^2\varepsilon' \tan \delta \quad \text{, where:} \qquad \text{(IV-7)}$$

P = power, in watts/cm^3

E = electric field in volts/cm

f = frequency in Hz

K = constant = 55.61×10^{-14}

$\tan \delta$ = dielectric loss tangent = $\varepsilon''/\varepsilon'$.

Because several approximations and assumptions were made in the development of these relations (e.g., assume that thermal equilibrium exists), the latter equation simply shows general relationships between the variables. For example, it is assumed that no chemical reactions take place, and that thermal equilibrium exists. The loss tangent is also defined for a nonionic material.

If convection and conduction losses are ignored, the heating rate is defined as

$$\frac{dT}{dt} = \frac{K f E^2 \varepsilon'(T) \tan\delta(T)}{\rho c_v} \qquad \text{(IV-8)}$$

where:

ρ = density

c_v = specific heat (it is stressed that ε' and $\tan\delta$ are dependent on both temperature and frequency).

The thermal energy deposited into the material is limited by the depth of penetration of the electromagnetic field into the material. This depth has been derived by Metaxas and Meredith (Ref. 561f) to be

$$D = \frac{1}{2\omega}\left\{\frac{2}{\mu_o \mu' \varepsilon_o \varepsilon'}\right\}^{1/2}\left[\left(1 + \left[\varepsilon''_{eff}/\varepsilon'\right]^2\right)^{1/2} - 1\right]^{-1/2} \qquad \text{(IV-9)}$$

where ω is frequency, in Hertz.

On a practical level, for a particular material, the size of the part determines the frequency at which it can be processed. At RF frequencies (several MHz to several hundred MHz), sizes are of the order of a meter. At microwave frequencies (GHz range) the sizes diminish to 20 cm or less. The latter is still of quite practical significance for commercial or military parts.

Bruce (Ref. 561g) has discussed several practical problems which may arise in microwave processing, such as thermal runaway, but these can be effectively avoided.

Microwave sintering is generally an improvement over conventional methods. It has the potential to provide homogeneous heating throughout the object as opposed to infrared heating where heat absorption starts at the surface (Ref. 594). Very close control over the heating process is also possible with microwaves, and very high temperatures (1500-2000°C) are achievable (Ref. 594). Microwaves have been shown to enhance

densification rates and lower the sintering temperature, which may result in lower energy utilization. Microwave plasma sintering of magnesia-doped alumina powder resulted in a sintering density in excess of 99% of theory in less than 2 minutes, and 99.9% in less than 10 minutes of processing (Ref. 593). Microwave sintering also reduced grain growth which may enhance a ceramic's mechanical properties (Ref. 585). The practical use of microwaves for the production of ceramic components is now being intensely studied in the United States.

B. OTHER PROCESSING AND MISCELLANEOUS EFFECTS

There has been growing interest in the use of microwaves during polymer and composite processing (Refs. 595-610). An increase in mechanical properties of 10% after an entire polymerization cycle of an epoxy matrix composite under the influence of microwaves has been reported (Ref. 601). The microwave processing of some polymeric materials decreased processing time from 1/3 to less than 1/10 of the original, provided homogeneous heating, and resulted in major energy savings in comparison with the conventional thermal process (Ref. 561b). The procedures are not fully understood yet, which has slowed use by industry. Microwaves have also been used to join ceramics, such as ceramic-glass-ceramic seals (Ref. 600). Isolated use has also been reported on the treatment of ores (Ref. 611) and of nuclear materials by microwaves (Ref. 612). The future use of microwaves seems to be limited only by the imagination of the user.

C. SURVEY RESULTS

Unlike other areas of this survey, Soviet work reported in the open literature on microwave effects has been extremely limited. This was quite surprising, since major new equipment for microwave processing is now available from the Soviet Union (Ref. 612a). The United States produced half of the surveyed literature. The breakdown by country is shown in Figure 7.

The interest on microwave effects has dramatically increased in the last three decades, as seen in Figure 8.

As mentioned, there has been a body of work (not included in this survey) on optical and biological effects. The areas of research included are shown in Figure 9. Much of this work has been on fabrication processes, with about 60% of that being on ceramic sintering.

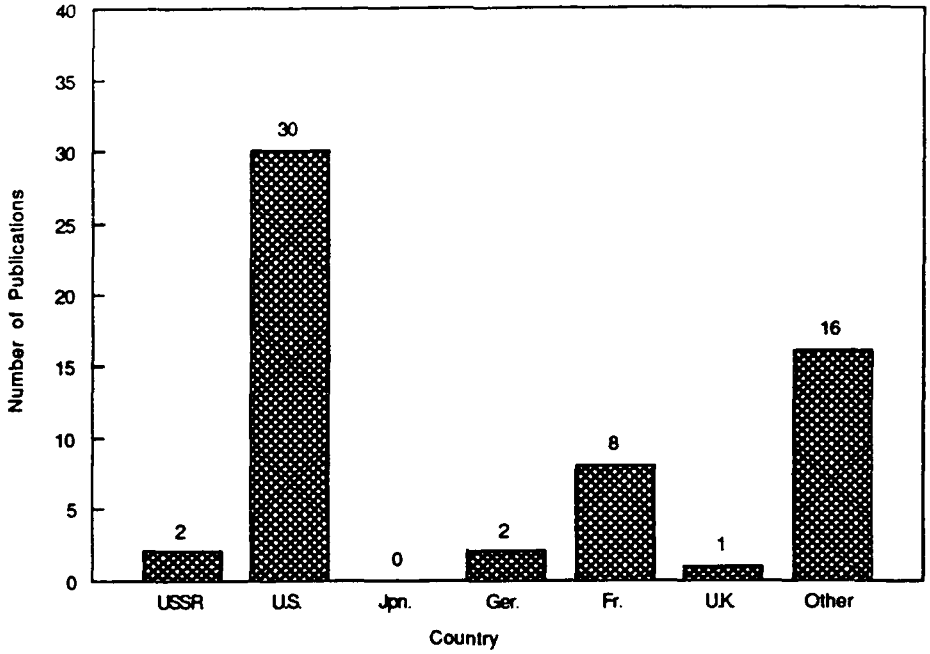

Figure 7. Published Research on Microwave Effects on Materials by Country (1960-1989)

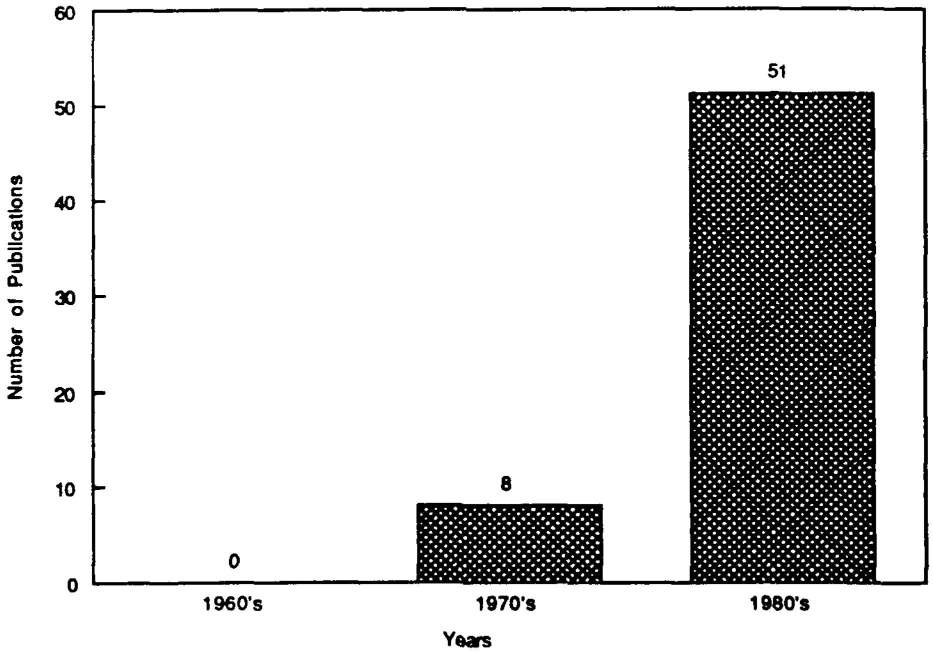

Figure 8. Published Rest arch on Microwave Effects on Materials by Decade

Sintering	(33, 56%)
Other Fabrication	(20, 34%)
Miscellaneous	(6, 10%)

Figure 9. Areas of Literature Emphasis (1960-1989)

V. MAGNETIC FIELD EFFECTS ON MATERIALS

The interest in magnetic field effects up to 1989, as reported in the open literature, can be described as moderate. Most of the referenced work deals with the effect of magnetic energy on mechanical behavior of metals (including metallic glasses) and alloys, and on polymers; none of it is comprehensive, and some is conflicting (Refs. 613-662). Recently, some effort has been directed towards the effect of electromagnetic fields upon the wear of materials (Refs. 657-662).

A. EFFECTS ON STRUCTURE AND MECHANICAL PROPERTIES

The magnetoplastic effect has been the main focus of the literature in this survey. Depending on the material and test conditions, several different mechanisms are proposed to be responsible for the effect. The cause of the magnetoplastic effect, however, is not yet fully understood or agreed upon.

Much of the study of magnetoplasticity has been done on both single and polycrystalline ferromagnetic metals. The changes in plastic flow in such metals have been attributed to the effect of the magnetic field on domain boundaries, which elastically interact with dislocations (Ref. 645). In a field of 0.25 Tesla, it was determined that there was a 10% increase in the flow stress in nickel (Ref. 656). Conversely, a 15% reduction in yield stress has been observed in nickel when placed in a variable magnetic field parallel to the extension axis (Ref. 632). The explanation attributed the cause to the oscillation of domain boundaries which unpinned dislocations and facilitated their movement along slip planes. High purity, polycrystalline iron placed in a high-intensity, constant magnetic field showed a 500% increase in creep rate (Ref. 657). Yield strength has, however, also been reported to increase in a magnetic field. Kononenko and Pustovalov reported that repeated loading of monocrystalline nickel up to its yield strength in a constant magnetic field at 4 °K resulted in domain structures and dislocations being formed and pinned (Ref. 656). The result was a maximum increase in yield strength of 20% (Ref. 656). An investigation by Bolshutkin, Denenko, and Ill'ichev studied the effect of full saturation of magnetization of polycrystalline nickel at 3.4 Tesla. They observed an increase of 10% in the flow strength of nickel, as was previously noted (Ref. 656). They also observed an increase in the

deformation hardening coefficient and deforming stress as the field increased. They attributed these changes to magnetostriction and Joule heating in the nickel by eddy currents, as well as to the domain-dislocation interaction (Ref. 656).

Studies of magnetoplasticity have been also conducted on nonmagnetic metals. In 1981, Lebedev and Krylovskiy observed an increase in the yield point of aluminum and lead in a magnetic field at low temperature (Ref. 645). They concluded that this was the result of an increase in electronic frictional force of dislocations. Tensile tests were performed at 4 °K with a force of 0.04 N for 25 seconds in a 3 Tesla field. For 1-2% deformation, the change in stress ($\delta\sigma = \sigma(H) - \sigma(0)$) grew and then fell rapidly (Ref. 645). The maximum increases of $\delta\sigma$ for aluminum, lead, and indium were 0.6, 0.45, and 1.3%, respectively (Ref. 645). For 4-5% deformation, the $\delta\sigma$ values became zero; the magnetic field had no effect beyond deformation greater than 5% (Ref. 645). The resistivity (p), which gradually rose as deformation increased, was used to estimate the electron relaxation time (t) as

$$t = p/A_{vF} \qquad \text{(V-1)}$$

where A is a constant of the material, and v_F is the Fermi velocity (Ref. 645). The term ωt (ω is the cyclotron frequency) can be calculated using,

$$\omega = 2\pi v_C \quad \text{(Ref. 730)} \qquad \text{(V-2)}$$

where v_C (109 Hertz) = 2.80H, and H is the magnetic field in kilogauss.

Lebedev and Krylovskiy's calculations showed that ωt fell an order of magnitude, from 10^2 to 10 at a deformation of 5% (Ref. 645). They then used theoretical models which define the change in mechanical characteristics under conditions of the superconductive transitions as a function of the electronic system of the crystal to show that the change in stress was associated with growth of the coefficient of electronic frictional resistance in the magnetic field (Ref. 645). The influence of the field, which is dependent on ωt, decreased as the amount of deformation grew, and was no longer effective on the plastic stress at $\omega t \approx 1$ (Ref. 645).

Experimentation on the magnetic effect on wear has been performed (Refs. 657-662). Some researchers reported increased wear resistance, while others have claimed increased wear rate. The effects and mechanisms of magnetic fields on wear are not yet understood, and they may be of importance for electromagnetic gun design.

Another change that takes place in a magnetic field at low temperatures that may affect mechanical properties of materials is the f.c.c. --> b.c.c. martensitic transformation. Fultz and Morris studied the effects of this transformation and determined that the changes in strength were of little engineering consequence. They were, however, useful in understanding the f.c.c. --> b.c.c. martensitic transformation (Ref. 646). In the magnetic field, a reduction in flow stress at small strains was recorded; but at large strains, an increase in work hardening and flow stress was noted. Reduction in elongation of the specimens was also observed.

B. PROCESSING AND MISCELLANEOUS EFFECTS

The effects of magnetic fields on the structure of materials, including polymers (filled and unfilled), during crystallization have been noted (Refs. 679-682). A magnetic field applied during the polymerization of an EDT-10 epoxy resin increased the degree of structural ordering and promoted the formation of crystalline regions in the amorphous material (Ref. 666). Molchanov et al. reported greater hardness and homogeneity in thermoplastics and thermosets subjected to a 0.8 Tesla field during processing. The hardness of Kapron increased from 4 N/mm^2 to 38 N/mm^2 (Ref. 679).

Another area of study has dealt with the effect of magnetic fields applied during annealing of materials (especially metallic glasses) on their electric and magnetic properties (Refs. 663-665, 667, 678, 683-704). Magnetic fields have been shown to improve the magnetic properties of such materials. Magnetic phase transitions also have been observed in strong magnetic fields (Refs. 705-708).

Other processes using magnetic fields have also been explored (Refs. 709-721). Application during vacuum metallization with closed field sputtering equipment reduced the source temperature and increased coating speed (Ref. 716). Magnetic fields have been used to orient macromolecules, which could improve the final quality of the polymers and reduce the production cost (Ref. 717). Isolated reports of the magnetic effect on optical properties of materials were also noted (Refs. 722-730). Finally, pulsed magnetic metal forming (Ref. 731) may offer new opportunities for welding and mechanical bonding of

similar and dissimilar metals and alloys, and for swaging of superconducting wires. With activities increasing in the use of electromagnetic power systems and other devices during the past few years, new interest in the fundamental behavior of materials in these environments can be expected.

C. SURVEY RESULTS

As mentioned, magnetoplasticity was the focus in the literature in the last three decades. Overall, the Soviet researchers once again accounted for much of the work done, slightly less than half. U.S. contributions were nearly 20%. Figure 10 reveals the level of effort by country.

As with microwave effects, the amount of research on magnetic effects on materials also grew rapidly in the last three decades, as seen in Figure 11.

Figure 12 shows the areas of emphasis, as revealed by the literature search.

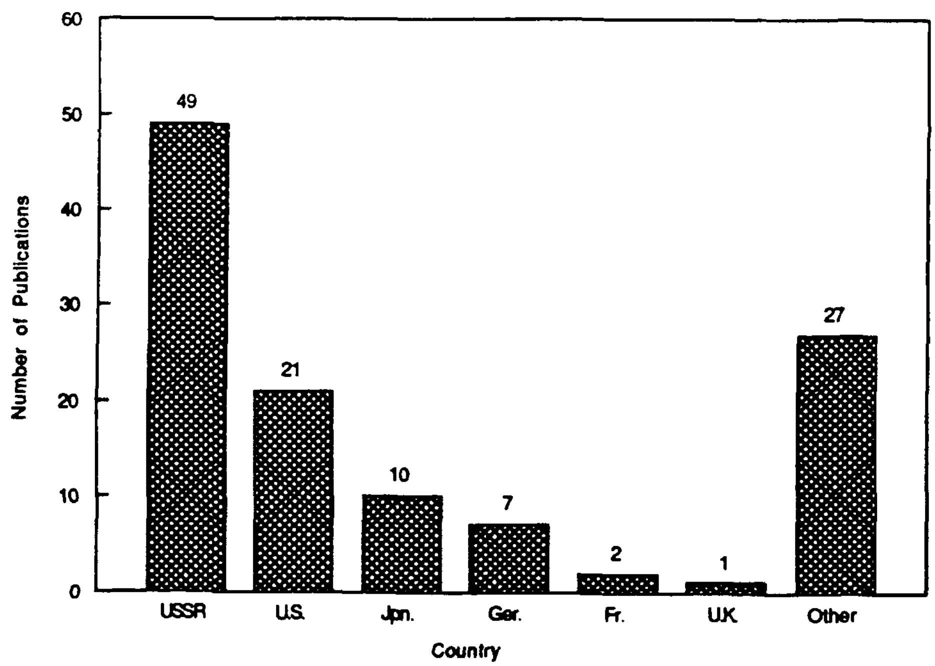

Figure 10. Published Research on Magnetic Field Effects on Materials by Country (1960-1989)

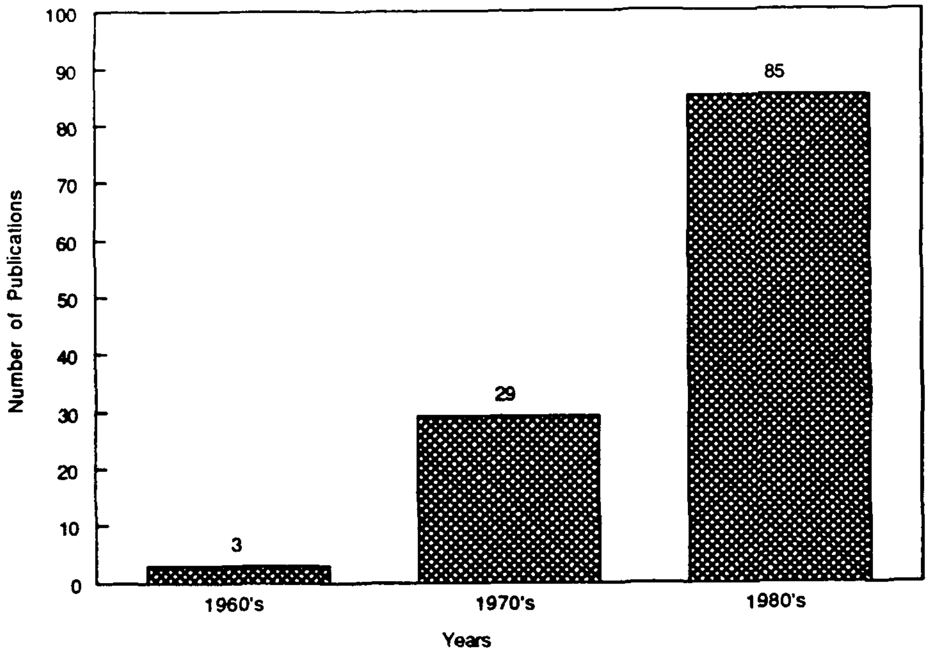

Figure 11. Published Research on Magnetic Effects on Materials by Decade

Magnetoplasticity	(50, 43%)
Solidification and Other Processing	(33, 28%)
Magnetic & Electric Properties	(22, 19%)
Miscellaneous	(12, 10%)

Figure 12. Areas of Literature Emphasis (1960-1989)

VI. CONCLUSIONS

This survey has determined that there has been a marked increase of activity and interest in the effects of electrical, magnetic, microwave, and acoustic energies on materials, especially in the last decade. While ultrasonic effects had been the focus of many studies prior to 1960, major scientific and technological activity has occurred in the area of electroplasticity, especially by Troitskii and Conrad. Indeed, the mechanisms of electroplasticity are better understood than the underlying bases of the other phenomena in this review.

Potential uses of electrical energy for materials processing have been shown to be advantageous. The effect of a high density current pulse (10^3 A/mm^2, 50 μs duration) has been demonstrated to have a large effect (10-40%) on load drop during tensile tests of zinc crystals (Ref. 29). The high density current pulse resulted in a large increase in plastic deformation (100-120%) during the same tests.

What this can mean in terms of practical consequences is that, since cavitation is retarded, processes such as superplastic forming can be extended to larger uniform deformations (Ref. 145). It is also expected, since cavitation often provides limits to deformation processing operations such as deep drawing, swaging, and extrusion, that the application of electric currents should be of significance in deformation processing by eliminating the need for intermediate annealing during processing. This has been found to be true (Ref. 139), but additional processing procedures should be explored for materials that are normally difficult to form by deformation, such as refractory metals and alloys.

Likewise, the concurrent application of high density current pulses (1.3×10^{-4} A/cm^2) during cyclic tests extended the fatigue life of copper by two- to three-fold (Ref. 146). What is particularly notable is that these pulses were only active 10^{-4} of the entire test time (Ref. 146). An additional benefit of the effects of electrical currents superimposed upon mechanical load cycling might be realized in electromagnetic guns. In this case, the fatigue lives of such guns can be expected to be much longer than the original design predictions, because both crack initiation and growth rate should be extended.

Finally, the industrial significance of the large effects of electric currents on the hardenability of steels also needs to be evaluated.

Ultrasonic treatment of stainless steels and aluminum alloys has resulted in increased hardness (20-40%) after only short exposures (30 seconds-5 minutes); the same amounts of hardening by natural aging would have taken much longer (≈ 24 hours) (Ref. 412). Similarly, large increases (218%, 10 hours) in yield strength have been recorded as well as creep rate reductions (≈ 60%, 30 seconds) (Ref. 412). Here again, the potential industrial savings to be gained through these treatments, in terms of energy and materials conservation, should be assessed.

Special attention has been given to wire drawing, as ultrasonic energy has been shown to reduce the drawing force (5-75% for drawing rates of 10-1000 feet per second) for copper and steel wires (Ref. 437). Tube drawing revealed similar results (1-30% reduction in force) for aluminum, steel, and titanium alloys. It also resulted in a smooth drawing (absence of stick-slip) which is not possible by conventional means.

Ultrasonic processing of other materials (other than metals) has been performed. Ultrasonic modification of cold-solidified plastic solutions during the processing of metal-plastic composites may reduce processing time by factors of 2-5 (Ref. 493). Ultrasonics have been demonstrated to be able to assist in machining a variety of products ranging from ceramics (Ref. 522) to graphite electrodes (Ref. 524) and composite helicopter blades (Ref. 513). Ultrasonic welding and other bonding methods assisted by ultrasonics have been in use for some years.

The ability of microwaves to provide rapid heating and very high temperatures (1500-2000 °C) provides such methods with the potential for use in a multitude of processes, such as sintering of ceramics. Microwave processing provides homogeneous heating, fast sintering times (1-10 minutes), and good control of the heating process. In addition, microwave sintering reduces grain growth, which may enhance the ceramic's mechanical characteristics (Ref. 585).

In addition to sintering effects, microwaves have been demonstrated to improve the mechanical properties (by 10%) of epoxy matrix composites during polymerization (Ref. 601). This effect is not as marked as the time savings achieved in processing of polymer-based materials. Microwave processing of some polymeric materials in 1/10 the normal time has been reported (Ref. 561b). The advent of equipment of greater versatility,

both in the United States and from the Soviet Union, should speed the practical industrial uses of microwave processing.

The magnetoplastic phenomenon is not yet fully understood, which impedes its possible applications to processing. Nonetheless, improvements in yield strength (20%) in single crystals of nickel in a magnetic field were reported, as was improved hardenability (Ref. 656). In the processing of polymers and magnetic metals, magnetic fields have provided enhanced structural ordering.

It was not surprising to find that Soviet research on the effects of electrical, magnetic, and acoustic waves on materials predominated in the world's open literature on these topics. In contrast, reports of microwave effects on materials from the Soviet Union were sketchy, at best. It appears likely, from the appearance of sophisticated Soviet microwave processing equipment in the commercial marketplace, that much work had been going on that was not published in the open literature. With increased access to scientific information becoming available in parts of the former Soviet Union, one can expect new light to be shed on the fundamentals of microwave effects on properties and processing of materials.

Enhancements resulting from processing with electrical, magnetic, microwave, and acoustic energies have been demonstrated to different degrees. Not only may these energies promote favorable structures and mechanical properties in metals, as has been known, but they may also offer new processing techniques for polymers, ceramics, and composites. In view of the fact that industry presently utilizes only a small portion of these enhancing energies, future efforts should focus on converting more of these effects from laboratory observations to industrial realities.

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